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**$J/\psi$  production as a probe of charge symmetry violations  
and nuclear corrections in parton distributions\***

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**Abstract**

We investigate the sensitivity of  $J/\Psi$  production in proton-neutron and proton-deuteron collisions to charge symmetry violations in the parton distributions as well as to nuclear corrections. It is found that the effects of charge symmetry violations in the quark distributions are confined to large  $x_F$  and difficult to measure in experiments currently being planned. However, from proton-deuteron experiments it should be possible to isolate nuclear corrections to the gluon distribution.

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# 1 Introduction

The production of heavy quarkonia has been studied quite extensively in deep-inelastic scattering (see e.g. ref.[1]) and in hadron-hadron collisions (see e.g. ref.[2, 3]). In the latter, at sufficiently high energy, the reaction proceeds through the annihilation of either a quark or gluon in one hadron with an antiquark or gluon in the other hadron. In principle one therefore has a probe of the quark and gluon distributions. For the quarks this process merely supplements the information obtained in Drell-Yan and deep-inelastic scattering, but for the gluons this is one of our few direct probes.

There have recently been suggestions that there may be a somewhat larger violation of charge symmetry in the minority valence quark distribution in the nucleon than one might naively have expected. At intermediate  $x$  this effect could be as large as 5% [4, 5]. It is important to try to test these ideas in Drell-Yan reactions [6]. Here we examine whether such an effect could induce a significant forward-backward asymmetry in the production of  $J/\Psi$  in proton-neutron collisions. As there has been no explicit calculation of a difference in the gluon distribution of a proton and neutron we also comment on this possibility.

In proton-deuteron collisions the forward-backward asymmetry of  $J/\psi$  production is sensitive not only to charge symmetry violations but also to nuclear modifications of the deuteron parton distributions. The latter could be investigated through experiments feasible at RHIC.

## 2 $J/\psi$ production in proton-neutron collisions

The production of charm-anticharm quark pairs proceeds in leading order in the strong coupling via gluon-gluon fusion or quark-antiquark annihilation. The corresponding cross sections for these subprocesses are [7]:

$$\hat{\sigma}_{gg}(c\bar{c}, M^2) = \frac{\pi\alpha_s^2}{3M^2} \left[ \left( 1 + 4\frac{m_c^2}{M^2} + \frac{m_c^4}{M^4} \right) \ln \left( \frac{1+\lambda}{1-\lambda} \right) - \frac{\lambda}{4} \left( 7 + 31\frac{m_c^2}{M^2} \right) \right], \quad (1)$$

$$\hat{\sigma}_{q\bar{q}}(c\bar{c}, M^2) = \frac{8\pi\alpha_s^2}{27M^4} (M^2 + 2m_c^2) \lambda, \quad (2)$$

where  $\lambda = \sqrt{1 - 4m_c^2/M^2}$ . The mass of the charm quark and the produced  $c\bar{c}$  pair is denoted by  $m_c$  and  $M$  respectively. The strong coupling constant  $\alpha_s$  is calculated at  $M^2$  using a QCD scale  $\Lambda = 0.177 GeV$ . Multiplying the cross sections of the QCD subprocesses with the parton distributions of

beam and target,  $f_i^b$  and  $f_j^t$ , yields the  $c\bar{c}$  production cross section

$$\frac{d^2\sigma(c\bar{c})}{dx_F dM^2} = \sum_{i,j} f_i^b(x_b) f_j^t(x_t) \frac{\hat{\sigma}_{ij}(c\bar{c}, M^2)}{s \sqrt{x_F^2 + \frac{4M^2}{s}}}. \quad (3)$$

In the center of mass frame Feynman  $x_F$  is defined as the fraction of beam momentum carried by the produced  $c\bar{c}$  pair and  $s$  stands for the squared center of mass energy. The light-cone momentum fractions of the active beam and target parton are

$$x_b = \frac{1}{2} \sqrt{x_F^2 + \frac{4M^2}{s}} + \frac{1}{2} x_F, \quad (4)$$

$$x_t = \frac{1}{2} \sqrt{x_F^2 + \frac{4M^2}{s}} - \frac{1}{2} x_F. \quad (5)$$

The  $J/\psi$  production cross section is proportional to the charm production cross section, integrated over the invariant mass of the  $c\bar{c}$  pair [7]. The integration limits are the thresholds for  $c\bar{c}$  pair production and  $D\bar{D}$  production:

$$\frac{d\sigma(J/\psi)}{dx_F} = F \int_{4m_c^2}^{4m_D^2} dM^2 \frac{d^2\sigma(c\bar{c})}{dx_F dM^2}. \quad (6)$$

The factor  $F$  specifies the fraction of events in which  $J/\psi$  bound states are formed. Despite being a simple model, such a description is well known to describe many features of heavy quark production, including the dependence of the  $J/\psi$  production cross section on  $x_F$  and the beam energy [2, 3]. Since it is of importance for our further discussion, we show in Fig. 1 the separate contributions to the  $J/\psi$  production cross section from gluon fusion and quark-antiquark annihilation. We take  $m_c = 1.5 \text{ GeV}$  and use the parton distributions of ref.[8]. At small  $x_F$  gluon fusion is by far the dominant mechanism, while for  $x_F > 0.6$  the  $q\bar{q}$  annihilation takes over.

To investigate charge symmetry violation we will now focus on  $J/\psi$  production in proton-neutron collisions. The corresponding production cross section involves the following combination of parton distributions

$$\begin{aligned} \hat{\sigma}_{q\bar{q}} & [u_p(x_b)\bar{u}_n(x_t) + \bar{u}_p(x_b)u_n(x_t) + \\ & d_p(x_b)\bar{d}_n(x_t) + \bar{d}_p(x_b)d_n(x_t)] + \\ \hat{\sigma}_{gg} & g_p(x_b)g_n(x_t) \end{aligned} \quad (7)$$

Here  $q_{p/n}$  are the quark distributions of the proton and neutron respectively and  $g_{p/n}$  the corresponding gluon distributions.

In an isospin rotated world  $J/\psi$  production in proton-neutron collisions becomes  $J/\psi$  production in neutron-proton collisions, i.e. the role of beam

and target is interchanged. If charge symmetry were exact, the difference between the corresponding cross sections would vanish. Interchanging the role of beam and target is equivalent to a sign change in  $x_F$ . Hence, the difference of the  $J/\psi$  production cross sections at positive and negative  $x_F$

$$\Delta\sigma_{pn}(x_F) = \left. \frac{d\sigma(J/\psi)}{dx_F} \right|_{x_F} - \left. \frac{d\sigma(J/\psi)}{dx_F} \right|_{-x_F} \quad (8)$$

is driven by charge symmetry violations only. In detail,  $\Delta\sigma_{pn}$  contains the following combination of parton distribution functions:

$$\begin{aligned} \hat{\sigma}_{q\bar{q}} \frac{1}{2} \Big\{ & (\delta u(x_b) - \delta d(x_b)) (\bar{d}(x_t) - \bar{u}(x_t)) + \\ & (\delta u(x_b) + \delta d(x_b)) (\bar{d}(x_t) + \bar{u}(x_t)) - \\ & (u(x_b) - d(x_b)) (\delta \bar{d}(x_t) - \delta \bar{u}(x_t)) - \\ & (u(x_b) + d(x_b)) (\delta \bar{d}(x_t) + \delta \bar{u}(x_t)) + \\ & [q \longleftrightarrow \bar{q}] \Big\} + \\ \hat{\sigma}_{gg} \Big\{ & \delta g(x_b)g(x_t) - g(x_b)\delta g(x_t) \Big\} \end{aligned} \quad (9)$$

We expressed the neutron distributions through the proton ones, using the definitions  $\delta d \equiv d_p - u_n$ ,  $\delta u \equiv u_p - d_n$  and  $\delta g \equiv g_p - g_n$ , and dropping the index “p”.

First we will consider contributions to  $\Delta\sigma_{pn}$  through charge symmetry violations in the valence distributions. The corresponding charge symmetry violating parts of the minority and majority distributions,  $\delta d^v = d_p^v - u_n^v$  and  $\delta u^v = u_p^v - d_n^v$  were extensively discussed in [4, 5]. We use the results of ref.[5] which were obtained within the framework of the MIT bag model. The magnitude of  $\delta d^v$  was found to be similar to that of  $\delta u^v$ . As  $d^v$  is generally much larger than  $u^v$  the fractional change in  $d^v$  is much greater. This can be easily understood, since one of the major sources of charge symmetry violation is the mass difference of the residual di-quark pair, when one quark of the nucleon is hit in a deep-inelastic scattering process. For the minority quark distribution the residual di-quark is  $uu$  in the proton and  $dd$  in the neutron. Therefore in the difference  $d_p - u_n$  the up-down mass difference enters twice. On the other hand, for the majority quark distribution, where the residual system is  $ud$ , both for the proton and the neutron, there is no contribution to charge symmetry breaking.

To calculate  $\Delta\sigma_{pn}$  we also need to know the flavor asymmetry of the quark sea,  $\bar{d} - \bar{u}$ , which enters in the first term of Eq.(9). We take a parameterization from ref.[9]:  $x(\bar{d}(x) - \bar{u}(x)) = Ax^{0.5}(1-x)^7$ , where the normalization  $A$  is fixed through  $\int dx(\bar{d}(x) - \bar{u}(x)) = 0.15$ . Such a parameterization is in good agreement with recently discovered violations of the Gottfried sum rule [14].

We normalize  $\Delta\sigma_{pn}(x_F)$  through the  $J/\psi$  production cross section in proton-proton collisions and present in Fig. 2 results for the ratio  $R_{pn}^{J/\psi} = \frac{\Delta\sigma_{pn}}{d\sigma(J/\psi)_{pp}/dx_F}$  at a center of mass energy  $\sqrt{s} = 40 \text{ GeV}$ . We find  $R_{pn}^{J/\psi} \approx -0.02$  at large  $x_F \sim 0.6 - 0.7$ . At smaller values of  $x_F$  (say below 0.5) the cross section difference  $\Delta\sigma_{pn}$  vanishes. This happens for two main reasons. At small  $x_F$  gluon fusion yields the major contribution to  $J/\psi$  production and quark-antiquark annihilation is of little relevance. Also  $\delta d^v - \delta u^v$ , which is much larger than  $\delta d^v + \delta u^v$  [5], enters  $\Delta\sigma_{pn}$  in combination with the small flavor asymmetry,  $\bar{d} - \bar{u}$ .

Charge symmetry breaking in the sea quark distributions has not been calculated yet. Nevertheless its influence on  $\Delta\sigma_{pn}$  can be estimated. In the MIT bag model the sea quark distributions are dominated by contributions characterized through residual four-quark states, after one quark is hit in a deep-inelastic scattering process [10]. By analogy with the valence quark case let us assume that a major source of charge symmetry breaking is the mass difference of the residual spectator states. Scattering on an antiquark which carries the same flavor as the majority quarks leaves a  $uuud$  or  $dddu$  residual four-quark state in the case of a proton or neutron target respectively. In case of an antiquark of minority flavor a  $uudd$  residual state occurs in both cases. Since the up-down mass difference enters twice in the first case but is absent in the second, it seems reasonable to assume  $\delta\bar{u} \gg \delta\bar{d}$ . In the following we will neglect  $\delta\bar{d}$ .

In Fig. 2 we also show  $R_{pn}^{J/\psi}$  for various values of  $\delta\bar{u}$  between  $0.01\bar{u}$  and  $0.10\bar{u}$ . Qualitatively we find minor changes to our former result where only charge symmetry breaking in the valence distributions was taken into account. We may therefore conclude that charge symmetry breaking in the quark distributions contributes to the difference of  $J/\psi$  production in the forward and backward direction only at large values of  $x_F$  ( $x_F \gtrsim 0.6$ ). Unfortunately this kinematic region is not accessible at the moment. In current measurements, using the neutron beam facility at FNAL, one is restricted to the region  $x_F > -0.1$  [11].

However the news is not all bad. Since charge symmetry violations in quark distributions do not contribute to  $R_{pn}^{J/\psi}$  at small  $x_F$ , it is an ideal place to look for charge symmetry violations in the gluon distributions. As we can see from Eq.(9), a (say) 1% charge symmetry violation in the gluon distribution,  $\delta g \sim 0.01g$ , can lead to  $|R_{pn}^{J/\psi}| \lesssim 0.02$ . No predictions exist up to now for charge symmetry violations in gluon distributions. Since a major part of the glue in hadrons can be viewed as being radiatively generated from quarks, charge symmetry violations in the quark distributions may in principle induce similar effects in the gluon distributions. However, since for charge symmetry violation in the radiatively generated glue the small

combination  $\delta d^v + \delta u^v$  is relevant, a large signal is not expected. If a large signal were seen it could only be attributed to charge symmetry violation in the non-perturbative glue, which would certainly be a surprise.

### 3 $J/\psi$ production in proton-deuteron collisions

In high energy processes deuterons are often used as a convenient source of neutrons. Furthermore, in the near future proton-deuteron collisions will be carried out at RHIC at center of mass energies between 50 and 375  $GeV$  and  $x_F > -0.5$  [11]. Therefore, at first sight it seems to be a good idea to investigate charge symmetry violations via  $J/\psi$  production in proton-deuteron collisions. However, as we will demonstrate below, nuclear modifications of deuteron parton distributions, which are interesting in their own right, are most likely to overtake the effects resulting from charge symmetry violations.

Let us assume that the parton distributions of the deuteron are related to those in the proton and neutron via

$$q_D(x) = (1 + \epsilon_q(x)) (q_p(x) + q_n(x)), \quad q = u, d, \quad (10)$$

$$g_D(x) = (1 + \epsilon_g(x)) (g_p(x) + g_n(x)). \quad (11)$$

In proton-deuteron collisions the difference  $\Delta\sigma_{pD}(x_F)$  of the  $J/\psi$  production cross sections measured in the forward and backward direction, involves the parton distribution functions:

$$\begin{aligned} & \hat{\sigma}_{q\bar{q}} \left\{ \frac{1}{2} (1 + \epsilon_q(x_b)) [ (\delta u(x_b) - \delta d(x_b)) (\bar{d}(x_t) - \bar{u}(x_t)) + \right. \\ & \quad \left. (\delta u(x_b) + \delta d(x_b)) (\bar{d}(x_t) + \bar{u}(x_t)) ] - \right. \\ & \quad \frac{1}{2} (1 + \epsilon_q(x_t)) [ (u(x_b) - d(x_b)) (\delta \bar{d}(x_t) - \delta \bar{u}(x_t)) + \\ & \quad \left. (u(x_b) + d(x_b)) (\delta \bar{d}(x_t) + \delta \bar{u}(x_t)) ] + \right. \\ & \quad \left. (\epsilon_q(x_t) - \epsilon_q(x_b)) (u(x_b) + d(x_b)) (\bar{u}(x_t) + \bar{d}(x_t)) + \right. \\ & \quad \left. [q \longleftrightarrow \bar{q}] \right\} + \\ & \hat{\sigma}_{gg} \left\{ (1 + \epsilon_g(x_b)) \delta g(x_b) g(x_t) - (1 + \epsilon_g(x_t)) g(x_b) \delta g(x_t) + \right. \\ & \quad \left. 2 (\epsilon_g(x_t) - \epsilon_g(x_b)) g(x_b) g(x_t) \right\} \end{aligned} \quad (12)$$

Clearly not all contributions to  $\Delta\sigma_{pD}$  arise from charge symmetry violation. There are also terms proportional to the difference of nuclear effects at  $x_b$  and  $x_t$ . In the following we will estimate their size and show that they are most likely to dominate over contributions from charge symmetry violations.

In Fig. 3 we show the light-cone momentum fractions  $x_b$  and  $x_t$  at which the beam and target parton distributions are probed for different  $x_F$  and for different center of mass energies  $\sqrt{s}$ . The invariant mass of the produced quark-antiquark pair is varied over the range  $4m_c^2 < M^2 < 4m_D^2$ . We observe

that at large values of  $s$  the dependence of  $x_{t/b}$  on  $M^2$  is rather small. While  $x_t$  decreases to very small values with increasing  $x_F$ ,  $x_b$  rises towards  $x_F$ .

Let us review the present knowledge of nuclear effects in deuteron distribution functions at light-cone momentum fractions probed in  $J/\psi$  production. Nuclear effects in quark distributions have been studied a great deal in deep-inelastic scattering processes (see e.g. [12, 13]). At small values of Bjorken  $x$  ( $x < 0.1$ ) shadowing effects in the deuteron of about  $(1 - 4)\%$  were predicted by many models and also recently observed (see [14, 15] and references therein). They suggest  $\epsilon_q(x) \sim (-0.01) - (-0.04)$  for  $x \sim 0.05 - 0.001$ . At  $x \sim 0.1$  shadowing disappears and the deep-inelastic scattering cross section for nuclear targets becomes slightly larger than the corresponding cross section for free nucleons. Such a behavior is also expected for deuterium, although small [16]. It suggests  $\epsilon_q(x \sim 0.1) \gtrsim 0$ . For  $x > 0.2$  binding effects cause a decrease of  $\epsilon_q < 0$ , while Fermi motion leads to a rise at  $x > 0.8$  (see e.g. [17]). Nuclear effects in gluon distributions are not so well established up to now. However momentum and baryon number conservation suggest that for  $x < 0.2$  they exhibit a behavior similar to that of the quark distributions – i.e.  $\epsilon_g \sim \epsilon_q$  [16].

The preceding discussion suggests that modifications of the deuteron parton distributions might easily be larger than the charge symmetry violating effects. For example, at a center of mass energy  $\sqrt{s} = 80 \text{ GeV}$  and  $x_F \approx 0.1$  we have  $x_t \approx 0.02$  and  $x_b \approx 0.12$ . While  $x_t$  is in the shadowing domain,  $x_b$  lies in the region where the deuteron parton distributions might be enhanced or are at least equal to the nucleon ones. The difference  $\Delta\epsilon_{q/g} = \epsilon_{q/g}(x_t) - \epsilon_{q/g}(x_b)$  can therefore easily range from  $\Delta\epsilon_{q/g} \approx -0.01$  to  $\Delta\epsilon_{q/g} \approx -0.03$ .

In contributions to  $\Delta\sigma_{pD}$  which are proportional to charge symmetry violations one may neglect nuclear effects to a good approximation. Then nuclear effects enter  $\Delta\sigma_{pD}$  via the difference  $\Delta\epsilon_{q/g}$  only. In Fig. 4 we show separately the contributions of gluon fusion and quark-antiquark annihilation to the ratio  $R_{pD}^{J/\psi} = \frac{\Delta\sigma_{pD}}{d\sigma(J/\psi)_{pp}/dx_F}$ , for different  $\Delta\epsilon_{q/g}$ , at a center of mass energy  $\sqrt{s} = 80 \text{ GeV}$ . For the charge symmetry violation in the valence distributions we again use the results of ref.[5], while the charge symmetry violation in the sea and gluon distributions are chosen to be zero. We find that at small values of  $x_F$  nuclear modifications of the gluon distribution in deuterium dominate  $R_{pD}^{J/\psi}$  or equivalently  $\Delta\sigma_{pD}$ . Therefore, if charge symmetry violation in the gluon distributions, which are accessible through  $R_{pn}^{J/\psi}$ , are small, nuclear modifications of the gluon distribution in deuterium can be investigated. Figure 4 demonstrates that, at large  $x_F$ , nuclear effects may easily dominate charge symmetry violation in the valence distributions.

## 4 Conclusion

We have discussed  $J/\psi$  production in proton-neutron and proton-deuteron collisions as a tool for investigating charge symmetry breaking and nuclear modifications of parton distributions. In proton-neutron collisions the difference of the  $J/\psi$  production cross section in the forward and backward direction,  $\Delta\sigma_{pn}$ , is solely due to charge symmetry violations in the nucleon. Charge symmetry breaking in the valence and sea quark distributions affect the cross section difference significantly only at large  $x_F \sim 0.6$ . At small values of  $x_F \lesssim 0.1$  a non vanishing result for  $\Delta\sigma_{pn}$  would be entirely due to charge symmetry violations in the gluon distributions. Corresponding measurements should be possible using the neutron beam facility at FNAL.

$J/\psi$  production in the forward and backward direction through proton-deuteron collisions will be possible at RHIC for a wide range of center of mass energies and Feynman  $x_F$ . The corresponding cross section difference is, however, not only due to charge symmetry violations but also to nuclear modifications of the deuteron parton distributions. As a consequence nuclear modifications of the gluon distribution in the deuteron could be investigated as well.

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Figure 1: Ratio of the quark (solid) and the gluon (dashed) contribution to the  $J/\psi$  production to their sum, for proton-proton collisions at  $\sqrt{s} = 40 \text{ GeV}$ .

Figure 2: Ratio  $R_{pn}^{J/\psi}$  at  $\sqrt{s} = 40 \text{ GeV}$ . The solid line includes charge symmetry violations in the valence quark distributions only. Different values for charge symmetry violations in the sea quark distributions are used:  $\delta\bar{u} = 0.01\bar{u}$  (dashed),  $\delta\bar{u} = 0.05\bar{u}$  (dotted) and  $\delta\bar{u} = 0.1\bar{u}$  (dot-dashed).

Figure 3:  $x_F$ -dependence of the light-cone momentum fractions  $x_b$  (solid) and  $x_t$  (dashed) for different center of mass energies. The shaded area indicates their dependence on the mass  $4m_c^2 < M^2 < 4m_D^2$  of the final  $c\bar{c}$  state.

Figure 4: Gluon (dashed) and quark (dotted) contributions to the ratio  $R_{pD}^{J/\psi}$  at  $\sqrt{s} = 80 \text{ GeV}$ . For the nuclear modifications of the gluon and quark distributions in the deuteron  $\Delta\epsilon_{g/q} = -0.01, -0.02$  are used. The solid line shows  $R_{pD}^{J/\psi}$  in absence of nuclear effects.







